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Water and Erosion Management with Multiple Applications of Polyacrylamide in Furrow Irrigation

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ABSTRACT

Polyacrylamide (PAM) in furrow irrigation water eliminates 94% of runoff sediment. Higher infiltration (15–50%) can result in upper-field overirrigation. We hypothesized that PAM would lengthen advance time, but that interactions with flow rate and wheel-track (WT) furrows would occur, influencing erosion and infiltration with potential for improved water management. A 2-yr study conducted on 1.5% slope Portneuf soil (Durinodic Xeric Haplocalcid) was irrigated with 10 g m^{-3} PAM in advancing 23 L min^{-1} furrow streams (reduced to 19 L min^{-1} after advance) (PAM treatment, P) or without PAM (control, C). Initial inflows in 1994 were 23 L min^{-1} (normal flow rate, N) or 45 L min^{-1} (high flow rate, H) with or without PAM. The application of PAM at 23 L min^{-1} (PN) increased 2-yr mean advance time 33% and reduced runoff soil loss 88% compared with controls (CN). Polyacrylamide applied at 45 L min^{-1} (PH) reduced advance time 8% and soil loss 75% compared with CN, whereas untreated 45 L min^{-1} inflows (CH) cut advance time 42% but raised soil loss 158%. The CH and PH raised infiltration 11 and 35% more than CN respectively. Polyacrylamide halted erosion in all furrows, but in WT furrows had no effect on advance time and little infiltration effect after two or three irrigations. This is mainly attributed to erosion and deposition increasing control-furrow wetted perimeters; accumulated PAM may also slightly affect seal conductivity. Polyacrylamide raised aggregate stability from 54 to 80% in 1993 and from 63 to 84% in 1994. In 1994, PAM reduced soil strength in furrows from 1.7 to 1.1 Mpa.

WATER SOLUBLE POLYACRYLAMIDES are potent tools for fighting furrow irrigation-induced erosion (Lentz et al., 1992; Lentz and Sojka, 1994,1996; Sojka and Lentz, 1994; Trout et al., 1995). Commercial products were registered in most western states by winter of 1994. In January of 1995, the USDA NRCS issued a western states interim conservation practice standard for the use of PAM to control furrow irrigation-induced erosion (Anonymous, 1995; Lentz et al., 1995). In 1996, an estimated 160 000 to 200 000 ha were treated in the western USA (Lilleboe, 1997), for a 5 to 10 million tonne soil conservation impact. Since the Environmental Quality Incentives Program (EQIP) can cost-share conservation management expenses, continued rapid growth of the use of PAM is anticipated.

Key aspects of PAM use are elimination of 94% (80–99% range) of furrow runoff soil loss with seasonal PAM applications of 3.5 to 8.0 kg ha^{-1} (3–7 lbs acre^{-1}) and a 15 to 50% infiltration increase (Lentz and Sojka, 1994; McCutchan et al., 1994; Trout et al., 1995; McElhiney and Osterli, 1996). Results were for PAM applied per the NRCS standard of 10 g m^{-3} PAM in the water first traversing a furrow, ceasing application at onset of runoff.

Early research focused on erosion control. Our experience with PAM since 1991 has also underscored PAM's infiltration effect. If farmers are unaware of PAM's tendency to increase infiltration, longer stream advance times and upper-field overirrigation could result. The combined erosion-halting and infiltration-increasing effects of PAM, however, have potential to improve furrow irrigation management if irrigators are aware of the soil and water interactions that result from PAM use.

The 'Russet Burbank' potato (*Solanum tuberosum* L.) is sensitive to stresses related to water, nutrients, and WT compaction. Infiltration changes systematically with field position in furrow irrigation, interacting with fertilizer practices and compaction and affecting potato yield and grade (Trout and Mackey, 1988a,b; Trout et al., 1994; Sojka et al., 1993a,b; Westermann and Sojka, 1996). These factors caused a large shift from furrow irrigation to sprinkler irrigation of Pacific Northwest potato. The same factors affect proper furrow irrigation management with PAM.

We hypothesized that PAM used in furrow irrigation would interact with wheel traffic; furthermore, PAM used with increased inflows might reduce the duration of stream advance yet still reduce erosion. A better understanding of these systematics can improve both erosion and water management. Our study documented the impact of multiple PAM applications on stream advance rate, net infiltration, runoff, soil loss, furrow-bottom soil aggregate stability, and soil strength at the surface of the furrow, as well as key interactions with wheel tracks.

METHODS AND MATERIALS

A 2-yr (1993–1994) field study was conducted near Kimberly, ID on adjacent fields to have similar initial conditions each year yet avoid disease problems with the second year's

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Abbreviations: C, control treatment; DOY, day of year; H, high flow rate; N, normal flow rate; NW, non-wheel; P, polyacrylamide treatment; PAM, polyacrylamide; ppm, parts per million; WT, wheel-track.

potato crop. Each potato crop was preceded by silage corn (*Zea mays* L.). Fields were Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcid). These soils have low organic matter, typically 10 to 13 g kg^{-1} and a moderate cation exchange capacity, typically 18 to 20 $cmol_c$ kg^{-1}. Soil pH is highly buffered (7.6–8.0) with a $CaCO_3$ equivalent of 2 to 8%. Electrical conductivity of saturated paste extracts ranges from 0.7 to 1.3 dS m^{-1} with an exchangeable Na percentage of 1.4 to 1.7%.

Field slopes were 1.5%. Corn stover was fall-plowed to 0.25-m depth. Fields were disked in spring to 0.1-m depth and roller-harrowed. Fields were bedded on 0.91-m centers prior to planting, simultaneously creating irrigation furrows using weighted 75° V-shaped furrow-forming tools. Furrows were ≈0.1 m deep (below original soil surface), and tapered flat-topped beds rose ≈0.2 m above the original soil surface (0.3 m from furrow bottom to top of the bed). Potato seed pieces were planted 0.15 m below the bed tops at a 0.3-m intrahill spacing on 10 May 1993 and 18 Apr. 1994.

The later planting in 1993 required only a single (preplant) bedding operation. Cultivation was performed on 26 May 1993. In 1994, the field was bedded before planting and a rebedding operation was performed 16 May.

Irrigation began when leaves emerged from the fourth stem node. The first irrigation was 2 June in 1993 and 26 May in 1994. Beds were sampled for soil water content prior to each irrigation. Irrigations were applied to meet seasonal evapotranspiration demands (as nearly as possible from furrow irrigation with water allocation shared among users), with shorter irrigation duration and longer intervals early and late in the season. Irrigations in midsummer, during peak demand periods, were typically twice weekly. Irrigations were by gravity flow and were alternated from WT to non-wheel (NW) furrows, with every other furrow in the field being either a WT or NW furrow. Thus, alternate sides of hills were wet at each irrigation. Late planting and a cool, wet early season resulted in a total of 22 irrigations in 1993 for a total duration of 186 h, compared with 28 irrigations and 260 h in 1994.

Irrigation water (0.5 dS m^{-1} electrical conductivity, 0.4–0.7 Na adsorption ratio) was applied using gated pipe with flow-regulating spigots. Pipe manifolds allowed simultaneous delivery of water at varied inflow rates and PAM-treated inflows to individual furrows. Furrow lengths were 181.5 m in 1993. In 1994, they were 126.8, 138.3, and 152.0 m for replications 1, 2, and 3, respectively (mean 139 m). Water and sediment calculations were done for each furrow individually.

Treatments in 1993 were untreated water or water treated with 10 g m^{-3} (10 ppm) PAM in the water advance. In the second year, irrigation treatments were added to widen the range of advance rates observed, allowing expanded evaluation of the potential for changing furrow irrigation management in conjunction with PAM use. Treatments in 1994 were as in 1993 but factored over two initial inflow rates (N and H). Inflow rates in 1993 were 23 L min^{-1} initially and reduced to 19 L min^{-1} following completion of furrow stream advance (N). Initial inflow rate was a treatment split in 1994; high inflow rate (H) was 45 L min^{-1} and normal inflow rate (N) was 23 L min^{-1}. As in the previous year, rates were reduced to 19 L min^{-1} following full advance. Minor variations in these protocols occurred occasionally to meet field exigencies. Irrigation duration varied among irrigations, depending on water needs, but were most often 8-h irrigations or occasionally 12-h irrigations. One 12-h irrigation of WT furrows, on day of year (DOY) 184 in 1994 was not monitored.

Polyacrylamide was Superfloc A836, provided by Cytec Industries, Wayne, NJ. This PAM has a molecular weight of 12 to 15 Mg $mole^{-1}$ for ≈150 000 monomer units per molecule, with a negative charge density of ≈18%.

In all cases, PAM was added only as water initially advanced down the furrow (or a few minutes longer); once runoff began, PAM application ceased, and only PAM-free water was applied for the remainder of the irrigation. Initially PAM was added to advance water of treated plots at 10 g m^{-3} (10 ppm), as per the NRCS standard (USDA NRCS, 1995). The 10 g m^{-3} PAM concentration during advance was achieved by injecting 2400 g m^{-3} PAM stock solutions into manifolds via peristaltic pumps. We PAM-treated all irrigations until furrows were covered by potato vines. In 1994, recognizing the very low sediment loss with 10 g m^{-3} PAM in the advance water, we reduced the PAM concentration of the season's remaining treated irrigations to 5 g m^{-3} on DOY 178, to determine if this lower application rate would continue to abate erosion.

Periodic inflow and outflow measurements and sampling were used to calculate field water and sediment balances. Sediment loss in runoff was determined using the Imhoff Cone technique (Sojka et al., 1992). Furrow net infiltration, runoff, sediment loss, and sediment concentration were calculated using furrow irrigation methodology and software (Sojka et al., 1994; Lentz and Sojka, 1995). One furrow was monitored per plot per irrigation.

We used a randomized strip plot design with two treatments and four replications in 1993 and four treatments and three replications in 1994. Some variables were characterized using a nested sampling scheme involving a nonrandom subfactor of distance along the furrow.

Soil depositional crusts in furrow bottoms were tested for surface penetration resistance and aggregate stability in both years before potato vines covered the furrows. We used two handheld flat-tipped surface penetrometers, one unit by Soil Moisture Corporation of Santa Barbara, CA, and the other unit by Geotester of Italy. Penetration resistances and 0- to 50-mm gravimetric soil water content were measured at the center of furrow bottoms in 1993 on DOY 166, 175, 193, 197, 203, 224, and 231 and in 1994 on DOY 173, 200, 236 on dry furrows before reirrigation. Penetration resistance was measured in both NW and WT furrows in 1993 but only in NW furrows in 1994. Water contents were measured in WT furrows in 1993 and in NW furrows in 1994. Three penetration resistances were determined with each instrument within ≈100 mm of one another at 62 and 120 m down the furrow.

Each year before vine closure, soil aggregate stability (Kemper and Rosenau, 1986) was determined on samples taken at 62 and 120 m along the furrow from the 0- to 20-mm depth. Samples were taken from both the center of the furrow bottom and from the upper edge of the wetted perimeter along the furrow sides.

Furrow width effects of erosion and deposition were measured at 62, 92, and 120 m along furrows in WT and NW furrows on 20 and 27 July 1993 and 7 and 11 July 1994.

RESULTS AND DISCUSSION

Runoff Sediment, Advance Time, and Infiltration

Using 10 g m^{-3} PAM in advancing furrow irrigation water (untreated water for the balance of an irrigation) reduced runoff sediment losses (Tables 1 and 2), much as previously reported for Portneuf soils (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka and Lentz, 1997). To maximize erosion abatement, PAM was applied both years in all irrigations prior to vine coverage. Applying PAM at 5 g m^{-3} beginning on DOY 178 in 1994 did not markedly reduce PAM effectiveness. The small rise in sediment loss in WT furrows on DOY 179 may indicate that reduced rate application warrant further evaluation. Total seasonal PAM application was 11.2 kg ha^{-1} in 1993 and 13.2 and 20.5 kg ha^{-1} in the normal and

Table 1. Total seasonal furrow inflow, outflow, infiltration and sediment loss, and mean advance time for non-wheel (NW) furrows, wheel-track (WT) furrows, or combined. Because WT and NW irrigations were separate events, all three presentations required separate statistical analysis (Table 2).

	Inflow			Outflow			Infiltration			Sediment loss			Advance times		
Treatment†	NW	WT	NW + WT	NW	WT	NW + WT	NW	WT	NW + WT	NW	WT	NW + WT	NW	WT	Mean
	mm									kg ha^{-1}			min		
								1993							
PN	331	295	626	59	101	160	272	195	466	124	71	195	157	91	121
	(24)†	(1)	(25)	(7)	(11)	(11)	(30)	(10)	(27)	(63)	(26)	(70)	(98)	(53)	(83)
CN	317	295	613	67	107	173	250	189	439	674	3705	4379	100	89	94
	(4)	(1)	(5)	(5)	(5)	(6)	(9)	(5)	(8)	(153)	(700)	(697)	(37)	(42)	(40)
								1994							
PN	718	553	1271	97	255	353	620	298	918	65	534	599	159	73	115
	(50)	(45)	(95)	(26)	(23)	(46)	(55)	(31)	(86)	(56)	(249)	(242)	(62)	(25)	(64)
CN	711	556	1267	177	225	402	534	331	865	2050	3015	5065	92	78	84
	(58)	(45)	(103)	(36)	(49)	(79)	(37)	(8)	(30)	(496)	(1150)	(770)	(68)	(24)	(50)
PH	946	643	1589	120	305	425	826	339	1164	25	1242	1268	108	47	77
	(33)	(52)	(85)	(87)	(45)	(122)	(61)	(23)	(41)	(20)	(1111)	(1130)	(49)	(17)	(47)
CH	866	635	1502	265	279	544	601	357	958	3991	9060	13051	50	48	49
	(36)	(52)	(83)	(48)	(51)	(97)	(35)	(15)	(22)	(2135)	(4723)	(6662)	(28)	(18)	(24)

† C is control, P is PAM application. H is high flow rate, N is normal flow rate.
‡ Standard deviation is shown in parentheses.

high flow treatments (PN and PH), respectively, in 1994. Consistent with previous findings, seasonal infiltration increased and runoff was reduced in PAM treatments compared with similar controls. In 1993, with identical CN and PN inflow management, PN increased advance time 28% (Tables 1 and 2), while reducing soil loss 96%. In 1994 PN increased advance time 37% compared with CN and reduced soil loss 88%. With higher inflows, however, PH reduced advance time 8%, yet still reduced soil loss 75% compared with CN. Without PAM, the high inflow CH treatment cut advance time 42% but boosted soil loss 158% compared with CN. High initial inflow rate per se in 1994 increased seasonal infiltration 11% in controls and 27% in PAM treatments. The PAM-treated high inflows (PH) increased infiltration 35% over controls at the normal inflows (CN). Control furrow sediment loss dropped drastically after DOY 190 in 1993 and DOY 180 in 1994, especially in NW furrows (Fig. 1).

Brown et al. (1995) showed a consistent seasonal pattern for furrow irrigation-induced erosion reduction for Portneuf soil, beginning around DOY 180. The NRCS standard (Anonymous, 1995) calls for full application (10 g m^{-3} in advancing furrow streams) for the first irrigation each season and whenever soil is disturbed by cultivation or traffic. It allows reduced rates of PAM application after the first or second full rate application. In the Pacific Northwest, after the initial one or two full-rate applications, farmers commonly apply PAM only as needed to prevent sediment loss. In this study, most of the seasons' erosion was prevented by PAM-treatment of WT furrows through DOY 200 in 1993 and DOY 180 in 1994. If PAM application had ceased by DOY 200 in 1993 and DOY 180 in 1994, seasonal application rates would have been 7.5 kg ha^{-1} in 1993 and 9.5 and 14.4 kg ha^{-1} in 1994 for PN and PH respectively.

The greater erodibility of irrigated WT furrows vs. NW furrows is known (Dickey et al., 1984; Brown, 1985; Sojka et al., 1993; Lentz et al., 1996). If PAM application had been restricted only to WT furrows, total application would have been 5.2 kg ha^{-1} in 1993 and 4.7 and 7.4 kg ha^{-1} for PN and PH respectively in 1994. Either reduced PAM application strategy, or a combination of them, would have halted most of the sediment loss seen in the corresponding control treatments.

Increasing the inflow rate is the most common strategy used to reduce infiltration opportunity time disparity from inflow- to outflow-end of irrigated furrows. This practice shortens advance times, but also accelerates erosion. We had equal irrigation set times among treatments in our study and reduced initial high inflows of all furrows simultaneously. Total inflows were similar for treatment pairs (CN vs. PN in 1993 and CN vs. PN or CH vs. PH in 1994). Changes in water application protocol in 1994, however, increased net water application for the control and PAM-treated high inflow treat-

Table 2. Statistics for total seasonal furrow inflow, outflow, infiltration and sediment loss, and mean advance time for non-wheel (NW) furrows, wheel-track (WT) furrows, or combined. Because wheel-track and non-wheel irrigations were separate events, all three presentations required separate statistical analysis.†

	Inflow			Outflow			Infiltration			Sediment loss			Advance time		
	NW	WT	NW + WT	NW	WT	NW + WT	NW	WT	NW + WT	NW	WT	NW + WT	NW	WT	Mean
									1993						
+/− PAM	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.0057	0.0020	0.0015	0.0445	NS	0.0394
									1994						
+/− PAM (P)	NS	NS	0.0071	NS	NS	0.0217	0.0097	NS	0.0082	0.0254	NS	0.0042	0.0014	NS	0.0018
N/H Flow (F)	NS	NS	0.0001	NS	NS	0.0077	0.0126	NS	0.0023	NS	NS	NS	0.0064	0.0001	0.0007
P × F	NS	NS	0.0109	NS	NS	NS	0.0469	NS	NS	NS	NS	NS	NS	NS	NS

† Probability > *F*; NS indicates a probability value > 0.05.

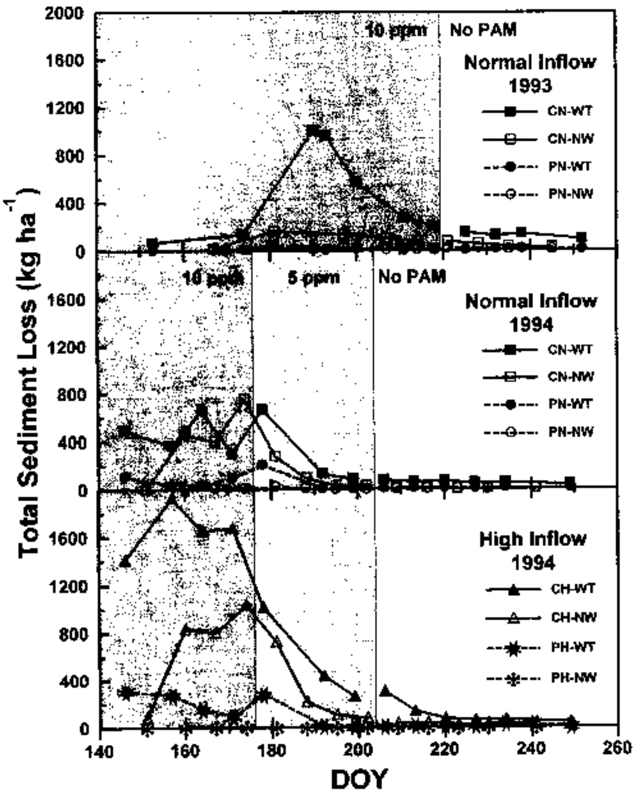

Fig. 1. Seasonal sediment losses per treatment per irrigation in furrow outflows in 1993 and 1994, as affected by PAM addition (P) or untreated water (C), normal (N) or high (H) flow rate, and wheel-track (WT) vs. non-wheel (NW) furrow.

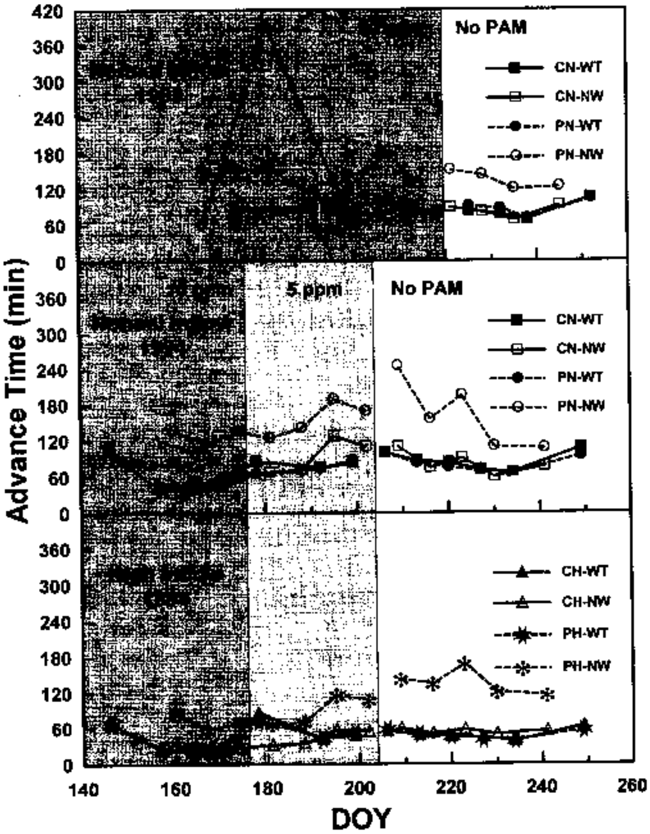

Fig. 2. Seasonal advance times in 1993 and 1994, as affected by PAM addition (P) or untreated water (C), normal (N) or high (H) flow rate, and wheel-track (WT) vs. non-wheel (NW) furrow.

ments (CH and PH) compared with the control and PAM-treated normal inflow treatments (CN and PN).

The increased net infiltration of H over N inflows probably resulted from two factors. With shorter advance times of H treatments, inflows could have been set back sooner than the N treatments; this was not done because adjusting individual furrows would have affected PAM concentration along the entire PAM manifold, which was serviced by a single PAM injection pump. Consequently, all inflow rates were changed simultaneously after stream advance in all furrows, regardless of treatment. Second, the slightly larger head, and greater wetted area in furrows during the high initial inflows probably increased infiltration during the high flow portion of the irrigation set. Water application differences between years resulted from differences in field dimensions, and a cool, wet 1993 growing season, with later planting and fewer and shorter irrigations required than in 1994.

Limiting analysis to season averages ignores patterns within treatments. Advance rate and infiltration differed between WT vs. NW furrows (Table 2; Fig. 2 and 3). Advance time was longer and net infiltration was generally greater with PAM treatment in NW furrows. However, advance time was nearly unaffected by PAM treatment of WT furrows, and in 1994 net infiltration of PAM-treated WT furrows was often slightly less than untreated WT furrows.

A few advance time and net infiltration anomalies bear explanation. Furrow net infiltration is a highly variable measurement (Trout, 1990). The low sediment loss of the first 1994 CH NW irrigation (Fig. 1) reflects failure of some furrows to advance during that irrigation. Since there is no way to reasonably show advance time (infinite) for the standard furrow length, no data point is plotted for that date's advance (Fig. 2), but runoff soil loss (Fig. 1) and infiltration (Fig. 3), which could be calculated, are shown. The long PN NW advance time on DOY 181 in 1993 (Fig. 2) resulted from the combined influence of cultivation immediately prior to irrigation and PAM treatment. The longer advance time of WT furrows in H treatments on DOY 178 in 1994 resulted from restricting all inflows on that date to the lower (N) flow rate due to water shortage.

The comparatively high WT furrow infiltration of DOY 206 in 1994 was due to a 12-h irrigation on that date preceded and followed by several days of 8-h irrigations. Higher infiltration early in the 1994 season was caused by long advance times; late in the season, vine intrusion increased the wetted perimeter, raising infiltration in the NW furrows. Interestingly, WT furrows remained incapable of high intake late in the season even with vine intrusion. We noted at planting that the wheel compaction pattern reached up the side of beds the full 0.1-m height of the furrow.

The PAM treatment enabled use of increased inflows in 1994 to obtain more uniform infiltration opportunity time (briefer advances) along furrows, while still reduc-

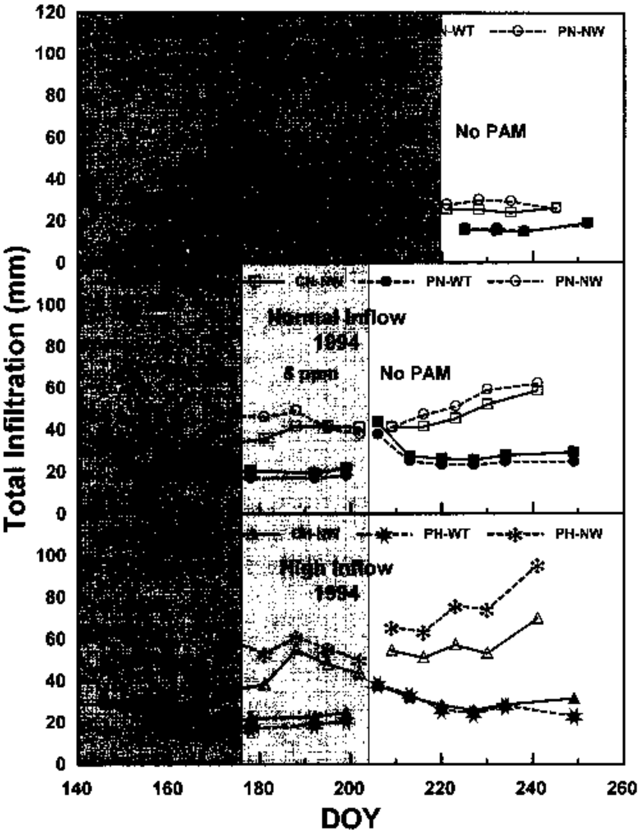

Fig. 3. Seasonal net infiltration amounts in 1993 and 1994 as affected by PAM addition (P) or untreated water (C), normal (N) or high (H) flow rate, and wheel-track (WT) vs. non-wheel (NW) furrow.

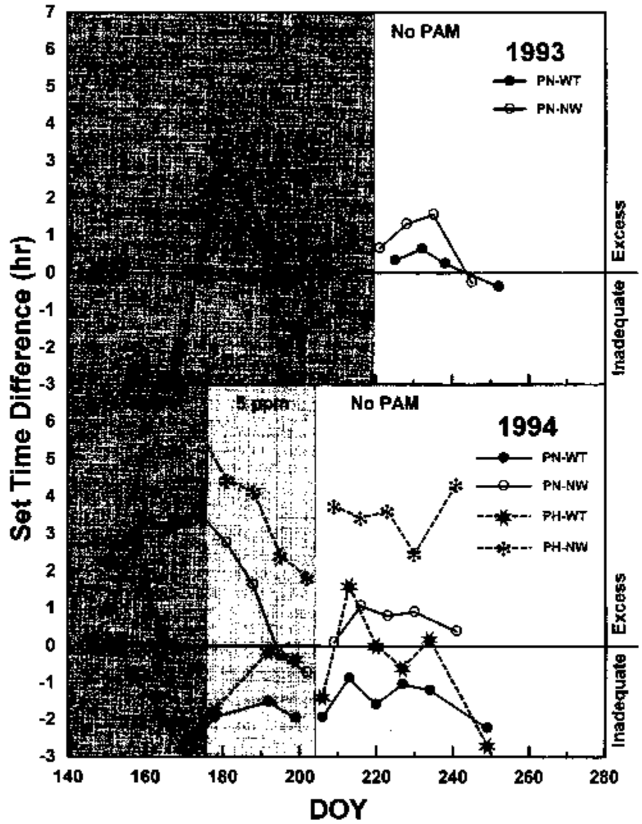

Fig. 4. Estimate of PAM (P) at normal (N) or high (H) flow rate and wheel-track (WT) or non-wheel (NW) effects on set-time excess or set-time deficit, relative to water amount delivered in the CN treatment of the respective WT or NW furrow each year, based on net infiltration of the CN treatment and the final infiltration rate of the corresponding PAM-treated furrows.

ing erosion. However, our data also show that farmers must be aware of the changes in infiltration from use of both PAM and higher inflows. If PAM is used without inflow adjustment, the greater infiltration opportunity time of upper vs. lower ends of furrows can be exacerbated. If PAM-treated water is applied at higher inflow rates (even employing the cutback irrigation method, used in this study), advance times will be shorter, but net infiltration will also be higher if irrigation duration is not reduced.

Increasing net infiltration is often desirable. When not, irrigation duration must be reduced to apply the desired water amount. Figure 4 shows the change in set duration of the PAM treatments relative to the CN treatment that would have been needed to infiltrate the same amount of water as CN, based on the steady state infiltration rate at the end of the irrigation set. Although PAM was very effective at reducing erosion in WT furrows, Fig. 3 and 4 show that PAM-treated WT furrows also had a slightly lower net infiltration than the controls. Figure 4 shows that the comparative infiltration reduction of PAM-treated WT furrows is greater late in the set and later in the season. Two explanations are possible; one relates to effects of accumulated PAM on surface soil pore conductivity; the other relates to changes in wetted perimeters of control or PAM-treated furrows.

Mitchell (1986) reported accelerated advance with PAM; however, his data were for a high montmorillonitic clay soil, using very high PAM application rates (25, 50, and 150 g m^{-3}). Our data suggest that if soil pore structure is already limited, for example from WT compaction, PAM treatment halts erosion but has no effect on advance (Fig. 2) and does not improve infiltration, or may even slightly lower infiltration (Fig. 3).

The trend in 1993 and 1994 toward lower set time excess of PAM-treated NW furrows as the season progresses (Fig. 4) could be evidence that accumulated PAM application gradually limits infiltration on furrows that have not recently been tilled. This may occur by altering apparent viscosity in pores (Malik and Letey, 1992; Letey, 1996), or by physically restricting water entry into the smallest pores. This trend has probably not been noted earlier because all furrow irrigation infiltration data reported to date for PAM-treated furrows came from either freshly formed furrows or only one repeat (retreated) irrigation. This finding underscores the prudence of conforming to the NRCS standard and avoiding overapplication of PAM, to prevent lowering infiltration in WT furrows.

There is an alternate, perhaps more plausible, explanation for gradual loss of comparative infiltration advantage with PAM on WT furrows. With numerous irrigations, furrows erode and alter their shape as detachment, transport, and deposition occur. Some field-scale hydraulic leveling of furrows also occurs from the

Table 3. The effect of PAM-treatment, field position, and wheel traffic on late season furrow width in two seasons of furrow irrigation. Field measurement locations were 62, 92, and 120 m along furrows, measured 20 and 27 July 1993 and 7 and 11 July 1994.

		1993			1994		
		Top	Mid	Bottom	Top	Mid	Bottom
PAM	Wheel-track	14.1	13.5	14.4	12.7	15.3	18.8
		(2.2)†	(1.9)	(1.8)	(2.1)	(1.8)	(1.8)
	Non-wheel	14.9	12.8	14.1	15.7	14.7	16.1
		(1.0)	(2.8)	(2.4)	(2.4)	(2.2)	(2.4)
Control	Wheel-track	21.9	24.0	24.3	27.8	29.6	28.4
		(4.2)	(2.6)	(2.9)	(3.1)	(1.8)	(2.5)
	Non-wheel	14.6	19.1	20.4	20.8	24.4	24.6
		(4.4)	(2.4)	(1.7)	(3.0)	(3.6)	(3.6)

† Standard deviation is shown in parentheses.

transport of soil at the upper furrow reaches to depositional areas lower in the field. In both years we noted nearly double the furrow-bottom width in control furrows compared with PAM-treated furrows (Tables 3 and 4) resulting from furrow side-cutting and deposition of eroded soil in furrow bottoms. The increased wetted perimeter was sufficient to raise control net infiltration of late season irrigations to the range of PAM-treated furrows. Furthermore, WT furrows, because of their higher erodibility or outflows, had wider furrow bottoms late in the season than NW furrows.

Thus, the loss of comparative infiltration advantage for PAM-treated furrows is probably an artifact of the increased wetted perimeter produced by greater erosional deposition in control furrows, especially WT furrows. This effect would be more pronounced in frequently irrigated crops (such as potato) or where erosional deposition is particularly severe.

Increased lateral wetting with PAM, reported in earlier studies, was not seen in this investigation. We concluded that the steeper beds and greater distance from furrow bottoms to the top of the beds in furrow-irrigated potato limited effects on lateral wetting. The 25% increase in lateral wetting (Lentz et al., 1992) for dry bean (*Phaseolus vulgaris* L.) used shallow furrows without raised beds.

Soil Properties

Erosion is a process determined by the interaction of a number of specific properties of the soil and the erosive fluid media. Soil cohesion and aggregate durability are important properties affecting this interaction. We assessed treatment effects on these properties by determining aggregate stability and soil strength (flat-probe penetration resistance) of surface soil along furrows (depositional crusts at the furrow bottoms).

Table 4. Statistics for the effect of PAM-treatment, field position, and wheel traffic on late season furrow width in two seasons of furrow irrigation.†

	1993	1994
+/− PAM	0.0003	0.0001
+/− Wheel	0.0001	0.0001
Location	NS	0.0007
PAM × Wheel	0.0001	0.0001
Pam × Wheel × Location	0.0420	0.0001

† Probability > *F*; NS indicates a probability value > 0.05. All factorials and interactions were tested individually and interactively; only those showing significant effects are listed.

Table 5. Percentage of water-stable aggregates as affected by PAM-treatment, date, and distance along the furrow.

	Furrow bottom, 8-12-93		Furrow side, 8-19-93	
Distance	PAM	Control	PAM	Control
62 m	82 (5)†	42 (8)	84 (5)	57 (8)
120 m	80 (5)	48 (13)	76 (6)	68 (8)
	Furrow bottom, 7-19-94		Furrow side, 7-19-94	
	PAM	Control	PAM	Control
62 m	90 (4)	36 (5)	92 (4)	69 (12)
120 m	76 (8)	47 (12)	85 (6)	78 (11)

† Standard deviation is shown in parentheses.

Soil samples from the upper few millimeters at the bottom and sides of furrows had greater aggregate stability in PAM-treated furrows than in controls (Tables 5 and 6). Aggregate stability of the control furrows was greater on the furrow sides than in the furrow bottom, but this positional effect was only about half as large as the aggregate stability enhancement attained with the PAM treatment. Increased aggregate stability of control furrow sides may result from upward movement of Ca solutes between irrigations.

Decreased PAM enhancement of aggregate stability at lower field reaches would have been expected, given the observation of Lentz et al. (1995b) that PAM concentration in the furrow stream decreases downstream as PAM is gradually adsorbed from the furrow stream onto the soil surface. Although aggregate stability values of control furrows were numerically greater in the lower field reaches and numerically less with PAM treatment, the effect was not statistically significant. Aggregate stability at a given position (furrow bottom or side) interacted with distance along the furrow. The increase in stability imparted by PAM was less on the furrow sides, where contact with water was sporadic, especially once PAM application was halted and inflow rates were cut back following initiation of runoff.

It is well known that soil aggregate stability increases from soil treatment with various PAM formulations, amounts, and application methods (Shainberg et al., 1992). Little or no data, however, are available for furrow irrigation-applied PAM applied in large volumes of water at low concentrations, or where PAM was only present briefly during initial inflows. The only soil ex-

Table 6. Statistics for the percentage of water-stable aggregates as affected by PAM-treatment, date, and distance along the furrow.†

	1993	1994
+/− PAM	0.0001	0.0001
Bottom/Side Position	0.0386	0.0001
62/120 m Distance	NS	NS
PAM × Position	0.0176	0.0008
PAM × Distance	0.0020	0.0248
Distance × Position	NS	NS
PAM × Position × Distance	NS	NS

† Probability > *F*; NS indicates a probability level > 0.05. In 1994 the effect of flow rate was found nonsignificant; therefore, flow data were pooled for further analysis.

Table 7. Effects of wheel traffic, distance down the furrow, water inflow rate and PAM treatment on depositional crust strength in two seasons. In 1993, soil water was only measured in wheel-track furrows.†

	CN		CH		Mean		PN		PH		Mean	
Distance	MPa	H_2O%	MPa	H_2O%	MPa	H_2O%	MPa	H_2O%	MPa	H_2O%	MPa	H_2O%
							1993 Non-wheel					
62 m	1.39						1.32				1.35	
	(0.64)						(0.81)				(0.72)	
120 m	1.35						1.35				1.35	
	(0.68)						(0.78)				(0.72)	
Traffic mean	1.37						1.33				1.35	
	(0.65)						(0.78)				(0.71)	
							1993 Wheel-track					
62 m	1.06	22.0					1.08	22.4			1.07	22.2
	(0.55)	(1.7)					(0.64)	(0.8)			(0.59)	(1.3)
120 m	0.87	27.5					0.79	22.9			0.83	25.2
	(0.59)	(5.3)					(0.41)	(2.7)			(0.50)	(4.7)
Traffic mean	0.96	25.7					0.94	22.7			0.95	24.2
	(0.57)	(5.1)					(0.55)	(2.2)			(0.55)	(3.2)
PAM mean	1.14						1.11					
	(0.63)						(0.68)					
							1994 Non-wheel					
62 m	1.17	16.9	1.19	21.2	1.18	19.0	0.56	16.4	0.66	17.0	0.61	16.7
	(0.75)	(9.6)	(0.73)	(17.2)	(0.72)	(13.7)	(0.26)	(7.9)	(0.44)	(8.9)	(0.35)	(8.1)
120 m	0.60	21.8	0.76	20.5	0.68	21.1	0.64	16.9	0.61	18.8	0.63	17.8
	(0.30)	(7.9)	(0.38)	(8.6)	(0.34)	(8.1)	(0.20)	(5.6)	(0.23)	(6.8)	(0.21)	(6.1)
Flow mean	0.88	19.3	0.97	20.8			0.60	16.6	0.64	17.9		
	(0.63)	(8.9)	(0.60)	(13.2)			(0.23)	(6.6)	(0.34)	(7.7)		
PAM mean					0.93	20.1					0.62	17.3
					(0.61)	(11.1)					(0.29)	(7.1)

† C is control, P is PAM application. H is high flow rate, N is normal flow rate.
‡ Standard deviation is shown in parentheses.

posed to PAM in furrow irrigation is that at the wetted perimeter of the furrow surface. Malik et al. (1991) documented that PAM does not migrate more than a few tens of millimeters through soil when exposed to dilute PAM application in leaching columns.

In our study, 10- to 20-mm thick depositional "crusts" formed along bottoms of both controls and PAM-treated furrows. The surface of the crust was grittier in appearance in PAM-treated furrows than controls, but hand lense examination of cross sections revealed no readily apparent differences. Soil strength of these crusts at the furrow bottom, quantified using two types of handheld penetrometers, were essentially the same.

Table 8. Statistics for the effects of wheel traffic, distance down the furrow, water inflow rate and PAM treatment on depositional crust strength and water content in two seasons.†

	Soil strength		Water content	
	1993	1994	1993	1994
+/− PAM	NS	0.0005	NS	NS
Distance	0.0252	0.0001	0.0414	NS
PAM × Distance	NS	0.0001	NS	NS
Traffic	0.0001	NA	NA	NA
Traffic × Distance	0.0477	NA	NA	NA
Traffic × PAM	NS	NA	NA	NA
Traffic × PAM × Distance	NS	NA	NA	NA
Flow rate	NA	NS	NA	NS
Flow rate × Distance	NA	NS	NA	NS
PAM × Flow rate	NA	0.0001	NA	NS
PAM × Flow rate × Distance	NA	0.0486	NA	NS

† Probability > F; NS indicates a probability value > 0.05; NA indicates not applicable. All factorials and interactions were tested individually and interactively; only those showing significant effects are listed.

Since the Geotester gauge readings were more easily resolved and somewhat more consistent, they alone are summarized (Tables 7 and 8). In 1993, seasonal mean strength was 1.26 MPa, with daily means ranging from 0.46 to 2.21 MPa across a gravimetric water content variation of 2.6 to 24.4%, with a mean of 13.8%. In 1994, seasonal mean strength was 0.78 MPa with daily means ranging from 0.44 to 1.26 MPa across a gravimetric water content variation of 10.2 to 27.5% with a mean of 13.8%.

In 1993, PAM did not significantly lower strength overall, nor was it significant interactively (Tables 7 and 8). Strengths were generally higher in the upper field. Interestingly, strengths were higher overall for NW furrows than WT furrows in 1993. In WT furrows, strengths were less in the lower field, where deposition was greatest.

In 1994, only NW furrow strengths were measured. The PAM treatment, field location, location × PAM interaction and flow rate × location × PAM interaction were all significant effects on strength as was the three-way interaction. Overall, PAM lowered strength. Control strengths were high in the upper field and low in the lower field. There was no strength reduction in the lower field for PAM plots, but that probably related to the already low PAM-treated strength in the upper field. Strength reduction with PAM was large in the upper field but smaller or inconsistent in the lower field at the N flow rate.

The pattern of strengths in 1994 suggests that in the lower field reaches, where some deposition had occurred regardless of PAM treatment, it was harder to distinguish strength effects. By contrast, in the upper reaches of control furrows, looser materials were removed by detachment and transport, exposing more compact soil below the immediate surface. Since more scouring occurred without PAM-treatment, the strengths tended to be higher in the controls at the upper end of the field. Both years' data suggest that strengths were greatest where soil along the bottom of the furrow remained consolidated and undisturbed longest or where consolidated soil was exposed by erosion.

Infiltration varies in response to solid phase phenomena that affect hydraulic conductivity, such as surface sealing. We concluded that the arrangement of primary soil particles and soil pores in the surface few millimeters differed between treated and untreated soil. The greater aggregation of surface soil in furrows and greater continuity of open pores from within the soil mass through to the surface could explain the difference in visual appearance of the wet surface seals and the greater infiltration rates of PAM-treated furrows. Similar conclusions were reached by others working in artificial systems where preapplied PAM was subjected to rainfall simulation (Shainberg et al., 1992). It is noteworthy in our study (and vis a vis the NRCS application standard) that the PAM effect on conductivity-impeding surface seals occurred at a PAM application rate of only 10 g m^{-3} and was sustained during high volumes of untreated water subsequently running over the furrow.

Sojka and Lentz (1995) observed that hydraulic sorting and bed creep or entrainment and deposition of soil caused surface seals affecting conductivity in both control and PAM-treated furrows. They noted however, that since PAM-treated furrow infiltration was higher than controls, there must be differences in the structure and porosity of the soil at the furrow surface caused by PAM.

We have consistently noted that after irrigation, the bottoms of PAM-treated furrows have a gritty appearance while still wet. By comparison, untreated furrows have a slick shiny appearance. The increased aggregate stability of surface soil in PAM furrows, and difference in wet appearance led Ross et al. (1996) and Sojka et al. (1996) in preliminary reports, to hypothesize that the structure of surface seals in PAM-treated furrows was more porous. At 24 h after an irrigation, they observed double the infiltration rate at 40- and 100-mm tension for PAM-treated furrows compared with controls. Our aggregate stability data further corroborates this proposed interaction.

CONCLUSIONS

Furrow irrigation can benefit from the management flexibility PAM provides while reducing erosion. Polyacrylamide can be used to greatly increase inflows yet still greatly reduce sediment loss. The smaller infiltration opportunity time disparity between upper and lower field ends achievable with use of higher inflow rates can help prevent overirrigation and leaching at upper ends of frequently irrigated fields. To fully realize this strategy requires reduction of inflows to minimum sustainable flows once runoff begins.

The use of PAM per se did not increase advance time or infiltration in WT furrows compared with untreated WT furrows after the first two to three irrigations. This is most likely due to furrow alterations occurring in the untreated furrows as a result of erosion, but may indicate some effect of PAM on pore conductivity with repeated application. This phenomenon deserves further study. Polyacrylamide applied at only 5 g m^{-3} after several 10 g m^{-3} applications continued to prevent erosion substantially compared with controls.

Measurements of strength of the depositional crust in furrows and of the aggregate stability of soil in furrow bottoms and along furrow sides support the conclusion that PAM's hydraulic and erosional effects result largely from structural stabilization of the thin surface veneer of soil in these locations, preventing surface sealing. Stabilization of structure is readily apparent in aggregate stability, but, as would be expected, is less consistently manifest in the strength of the furrow-bottom depositional crust. The increase in aggregate stability prevents formation of hydraulic conductivity-restricting surface seals that result when aggregates break down, dispersing clay that blocks small pores. Greater aggregate stability is also associated with maintenance of surface roughness and resistance to erosion. While the importance of these phenomena have been demonstrated before for rainfed erosional processes (with splash-related energy, detachment and transport), few if any reports have documented these effects with furrow irrigation-induced erosion, which has no splash component.

Analysis of the seasonal application pattern of PAM and resulting erosion in this study confirm that most of the season's erosion can be avoided in furrow irrigation with only a few kilograms per hectare of PAM application early in the season applied in sequential irrigation events.

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